EEE Parts Guidelines for SmallSat Missions

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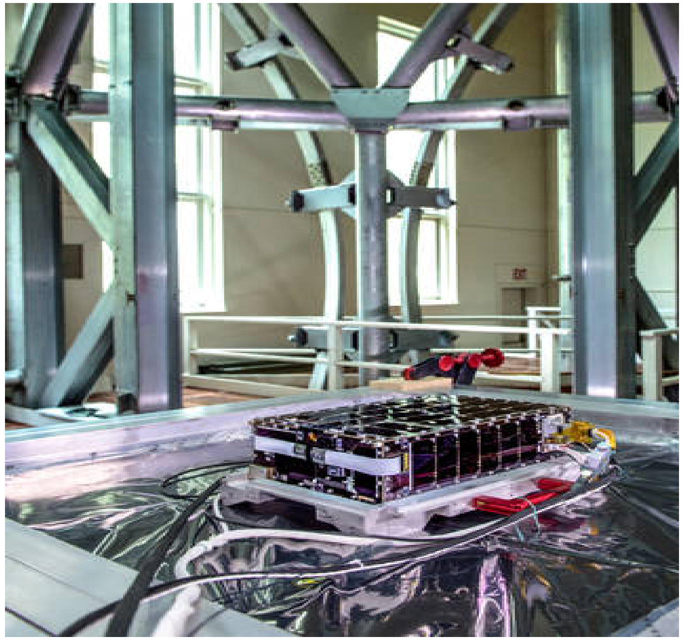
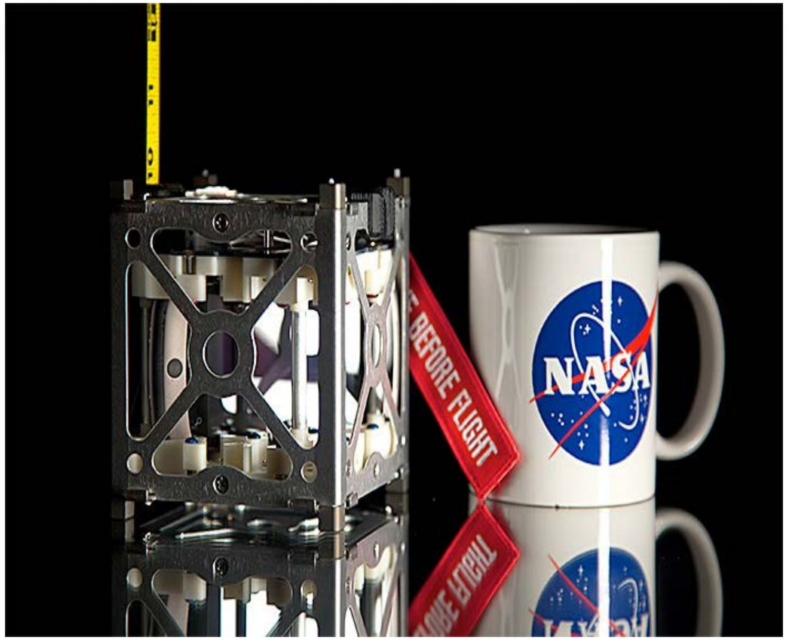
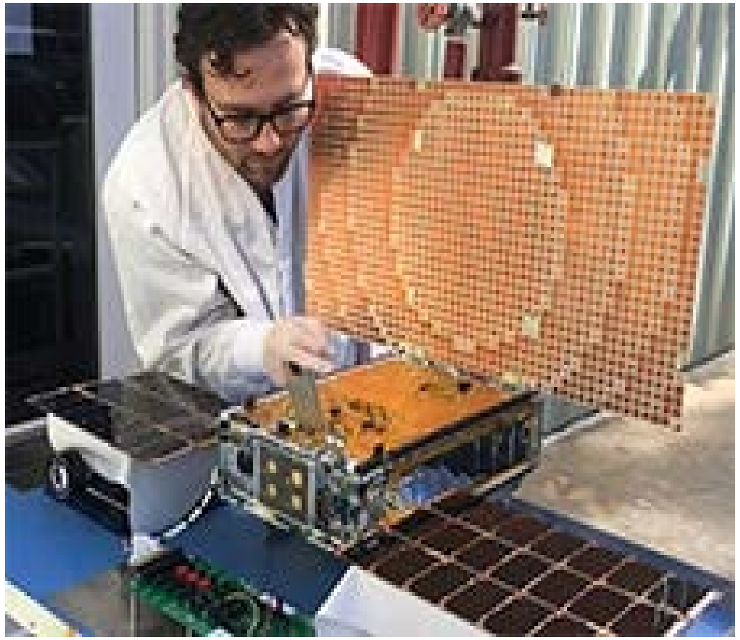
Emergence of SmallSats







Benefits compared to traditional NASA Missions:

- Shorter development times
- Lower costs
- Opportunities to ride share

Drawbacks when compared to traditional NASA Missions:

- Lack of reliability guidelines and standards
- Lack of sound reliability history
- Inconsistent mission success and failure rates

What Does This Mean for EEE Parts?

- Size
- Weight
- Power
- Cost
- Lead Time

May Be

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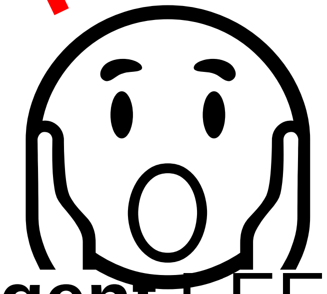
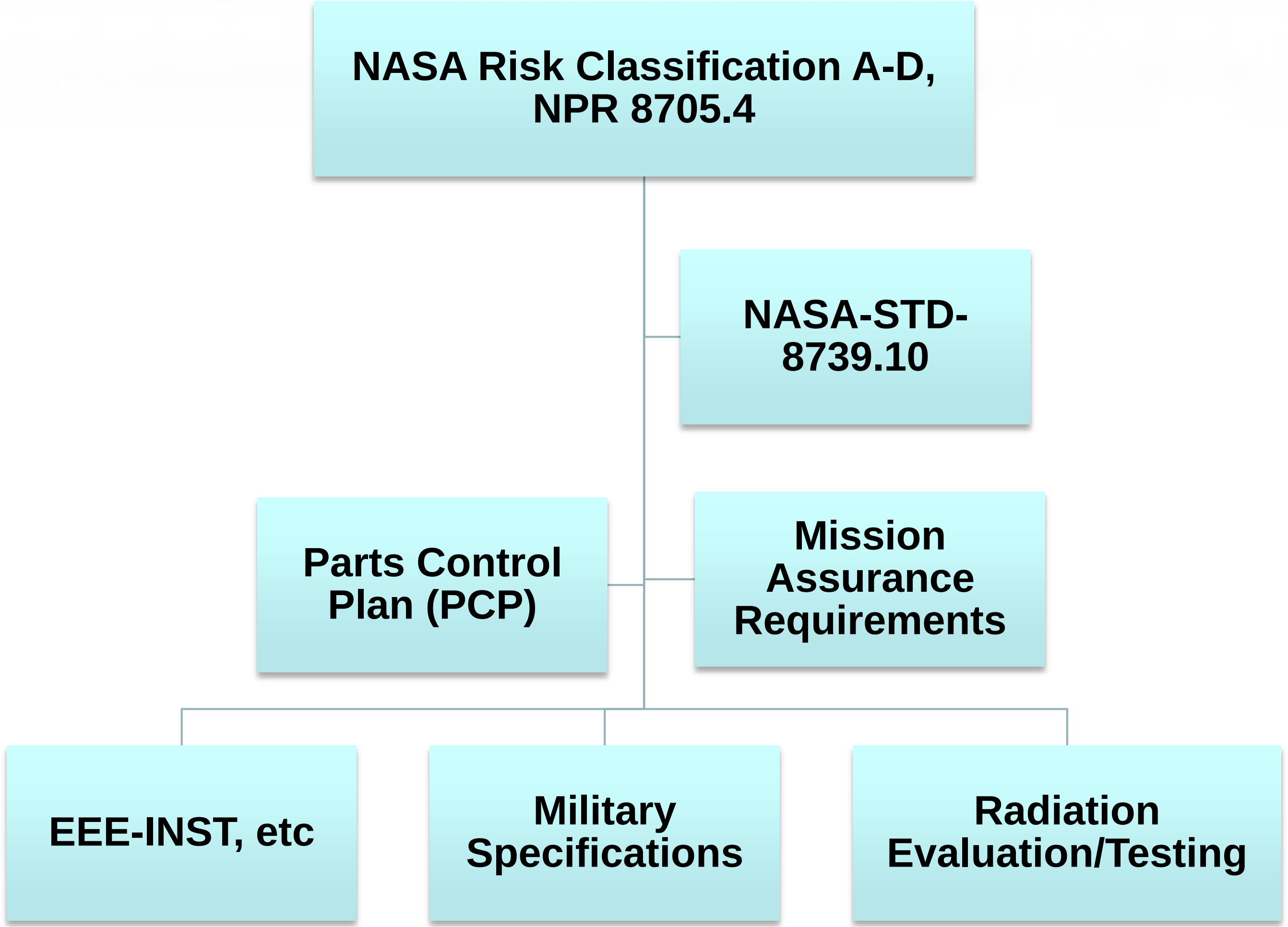


- Reliability

Takeaway: Alternate but **Intelligent** EEE parts approaches are required for most SmallSat Missions

Traditional Approach to EEE Parts



Pros:

- EEE parts are qualified over broad end use applications
- Established quality control system
- Traceability
- High success rate in flight applications

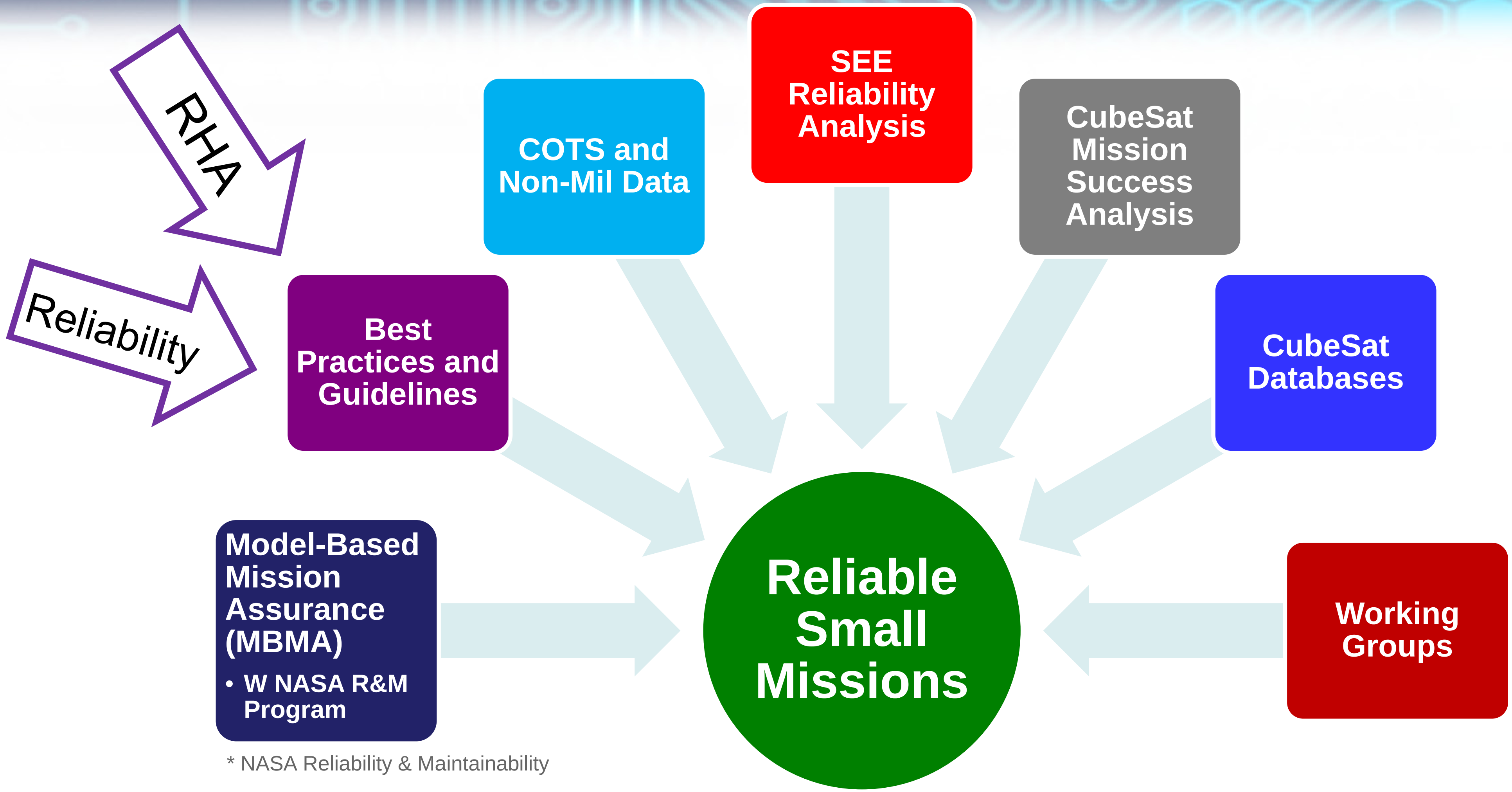
Limitations of Traditional Approach for SmallSat Missions

- **Cons with traditional NASA approach when considering SmallSats:**
  - Cost prohibitive
  - Schedule prohibitive
  - Performance lags commercial options
  - Nebulous correlation with project risk posture
- **Takeaway:**
  - SmallSat schedule, budget, size, mass, and other resource constraints dictate that the traditional NASA EEE parts paradigm is inappropriate (and in many cases **IMPOSSIBLE**) for SmallSats
  - An alternative EEE parts selection approach based on risk trades at the system and component level should be explored

SmallSat Guidance Needed

- **Parts Selection**
  - Commercial? Automotive? Industrial Grade? Anything goes?
- **Screening**
  - Screening? Qualification? Destructive Physical Analysis? Board Level Testing?
- **Radiation Susceptibility**
  - Is data available? Is Testing required? Heavy Ion? Total Ionizing Dose?
- **Risk Assessment**
  - How to rack all this information up and assess what is "Acceptable Risk"?

NEPP - Small Mission Efforts



* NASA Reliability & Maintainability

Enter the original 3x3…

Criticality	Low	Medium	High
High	Level 1 or 2 suggested. COTS upscreening/ testing recommended. Fault tolerant designs for COTS.	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.	Level 1 or 2, rad hard recommended. Full upscreening for COTS. Fault tolerant designs for COTS.
Medium	COTS upscreening/ testing recommended. Fault-tolerance suggested	COTS upscreening/ testing recommended. Fault-tolerance recommended	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.
Low	COTS upscreening/ testing optional. Do no harm (to others)	COTS upscreening/ testing recommended. Fault-tolerance suggested. Do no harm (to others)	Rad hard suggested. COTS upscreening/ testing recommended. Fault tolerance recommended

Environment/Lifetime

Defining Criticality

Fault Tolerance				
Fault Tolerance	Minimal Fault Tolerance, Single String Systems	Low	Medium-High	High
	Fault Tolerance built in, but requires interrupting operations	Low	Medium	Medium-High
	Inherent Fault Tolerance, Faults can occur without impacting operations	Negligible	Low-Medium	Low-Medium
		Telemetry Data or Secondary Science Products	Primary Science Data, Mission Reqs	Mission Critical, Impact to Spacecraft Health
		Application		

Example: Temperature Sensor

Case 1) Used for telemetry, multiple sensors installed.

Case 2) Used to monitor temp of an amplifier, for gain error correction.

Case 3) Used to monitor solar panel temperatures and provide feedback loop for active cooling system and SC orientation.

Defining Environment/Lifetime

Environment				
	High Radiation +/- 40C thermal profile 80C ambient temps	Medium-High	Medium-High	High
	Med Radiation +/- 20C thermal profile 60C ambient temps	Low-Medium	Medium	Medium-High
	Low Radiation +/- 5C thermal profile 30C ambient temps	Low	Low-Medium	Low-Medium
		Less than 1 year	1-3 year	Greater than 3 years
		Lifetime		

- Numbers/quantities are suggestions, may vary based on mission profiles.
- Purpose is to show some factors to consider in assessing mission specific environment/lifetime stresses.
- Within a given mission different boxes/parts could have different thermal profiles.

Putting It All Together

Parts Selection and Testing Guidelines Based on Criticality and Environment

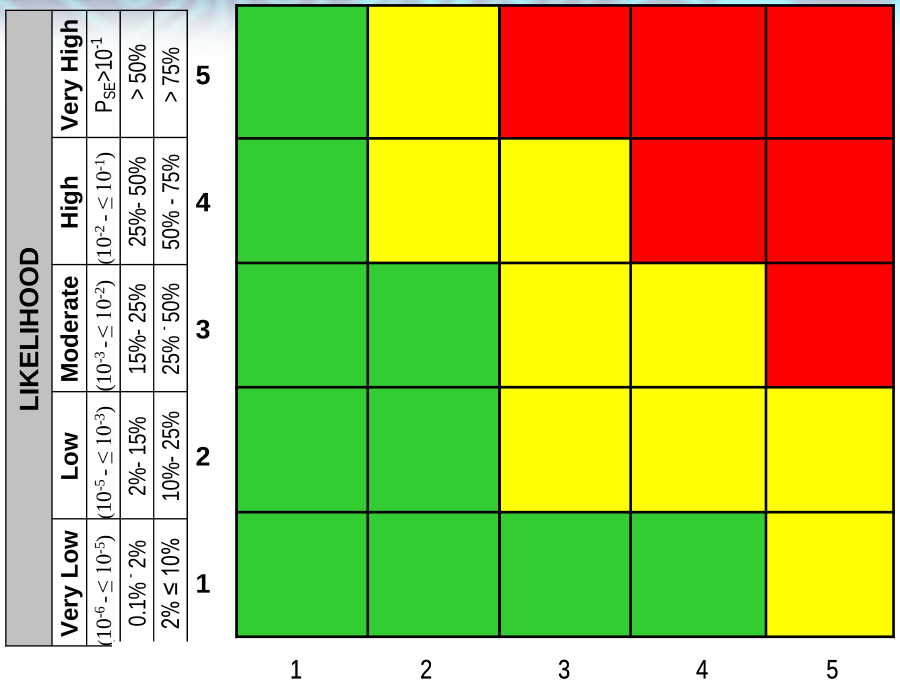
Criticality		Low Stress, Short Duration	Moderate Stress, Moderate Duration	High Stress, Long Duration
Criticality	Spacecraft Bus, Critical Applications, Minimal Fault Tolerance Available	COTS Parts Acceptable, Part Level DPA, Enhanced Board Level Testing	MIL Parts Preferred Part Level DPA, Part Level Screening	MIL Parts Required, Part Level DPA Part Level Screening, Lot Acceptance Testing,
	Science/Mission Requirements, Fault Tolerance with Minimal Impact	COTS Parts Acceptable, Enhanced Board Level Testing	COTS Parts Acceptable, Part Level DPA, Enhanced Board Level Testing	MIL Parts Preferred Part Level DPA, Part Level Screening
	Telemetry Applications, Inherently Fault Tolerant Systems	COTS Parts Acceptable, Standard Board Level Testing	COTS Parts Acceptable, Enhanced Board Level Testing	COTS Parts Acceptable, Enhanced Board Level Testing

Environment/Lifetime

Mission Specific Risk Trades

- Risk identified during the parts selection process should flow up to the mission level
- NASA GSFC follows an approach where risks are classified by likelihood and consequence to the mission
  - Governed by GPR 8705.4

- Following this process allows for universal language with respect to EEE parts
  - *Risk in terms of likelihood and consequence*



Safety (S)	Negligible or no impact	Could cause minor first aid treatment	May cause minor injury or occupational illness, minor property damage	May cause severe injury or occupational illness major property damage	May cause death or permanent injury or destruction of property
Technical (T)	No KPP impact / no tech required	Minor impact to KPP / mod to existing tech required	Moderate impact to KPP/ some new tech required	Significant impact to KPP/ mod new tech required	KPP cannot be met / major new tech required
Cost (C)	≤ 1% increase	≥ 1% but ≤2% increase	≥2% but ≤ 5% increase	≥5% but ≤8% increase	> 8% increase
Schedule (SC)	No slip	Non-critical slip 1-2 mo	Non-critical slip 2-3 mo	Non-critical slip 3-4 mo	Slip on critical path, launch date
CONSEQUENCES					

Bonus: Commodity Based Tips

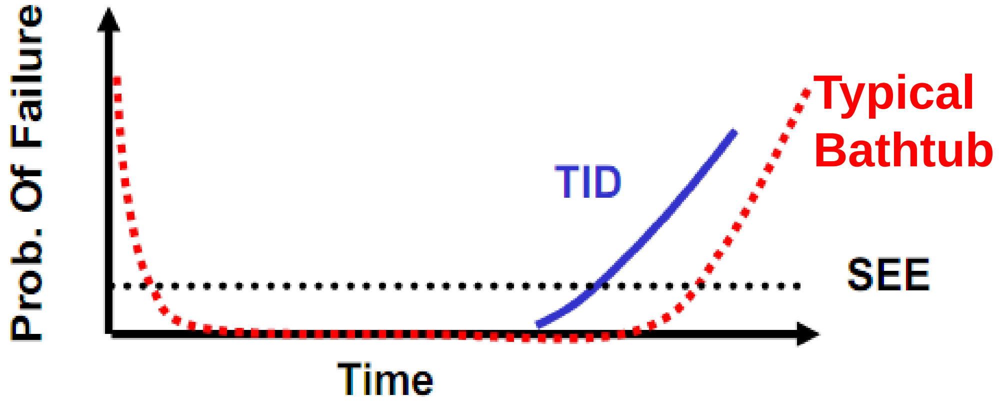
- Watch out for common mode failure mechanisms- redundancy doesn't help if all parts are susceptible to the same failure mechanism!
- For Example
  - Don't abuse COTS capacitor offering- choose conservative values. Hand Soldering can damage ceramic chip caps.
  - Be aware of *risky* materials- tin whiskers like COTS connectors.
  - Relays, Switches, Connectors (electro-mechanical parts) are problematic- Testing parts here offers good return on investment.

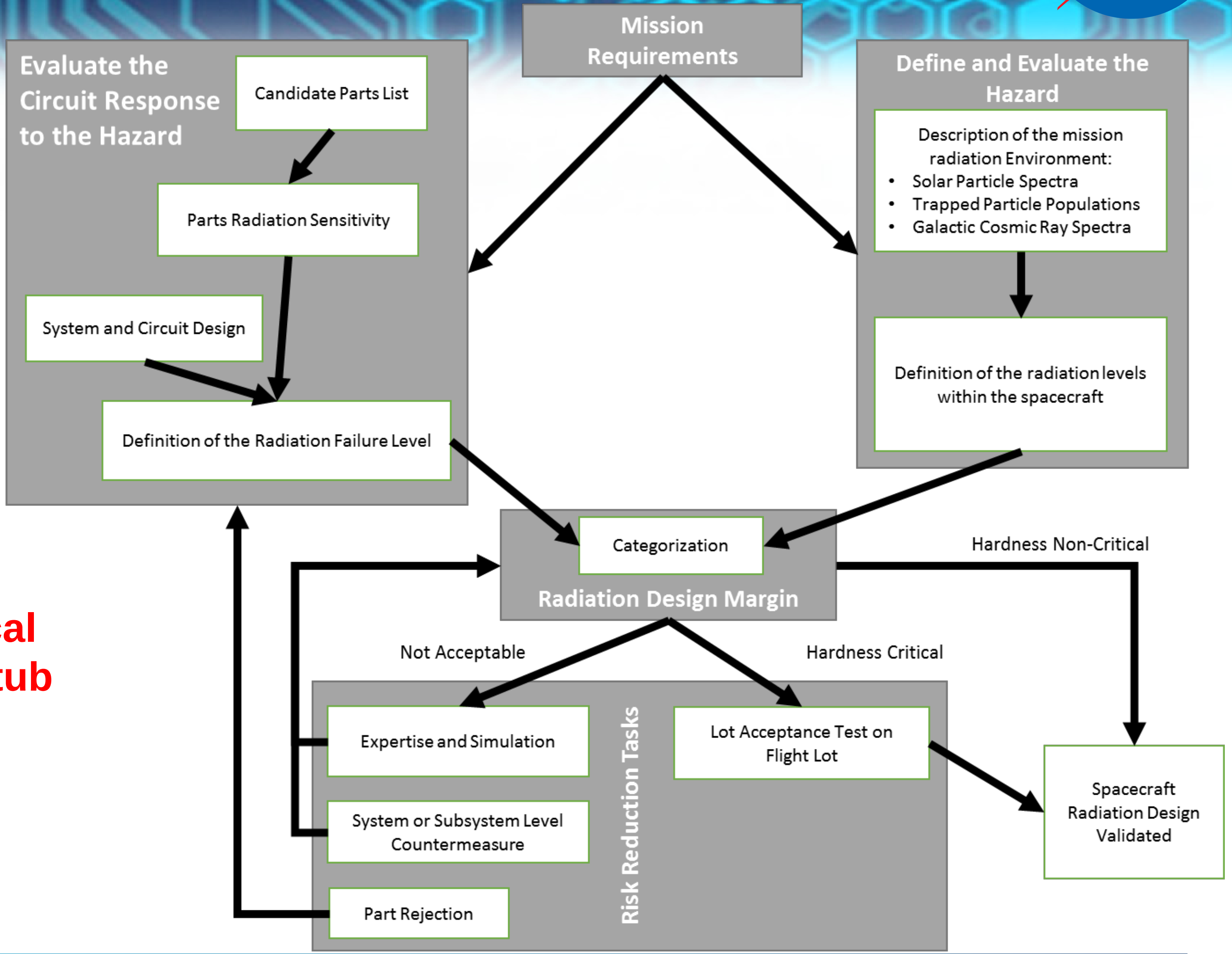
But What About Radiation Effects?

Materials	Device Physics	Electrical Engineering	Systems Engineering	Space Physics
• Material Property degradations with radiation • Energy loss in materials	• Charge transport • Device Process Dependencies • Charge dependency of device operation	• Part to part interconnections • Understanding circuit response • Device functions and taxonomy	• Requirements • System Level Impacts • Understanding interconnections • Understanding functionality	• Space weather • Environment models/modeling • Radiation Sources and variability

Radiation Hardness Assurance (RHA)

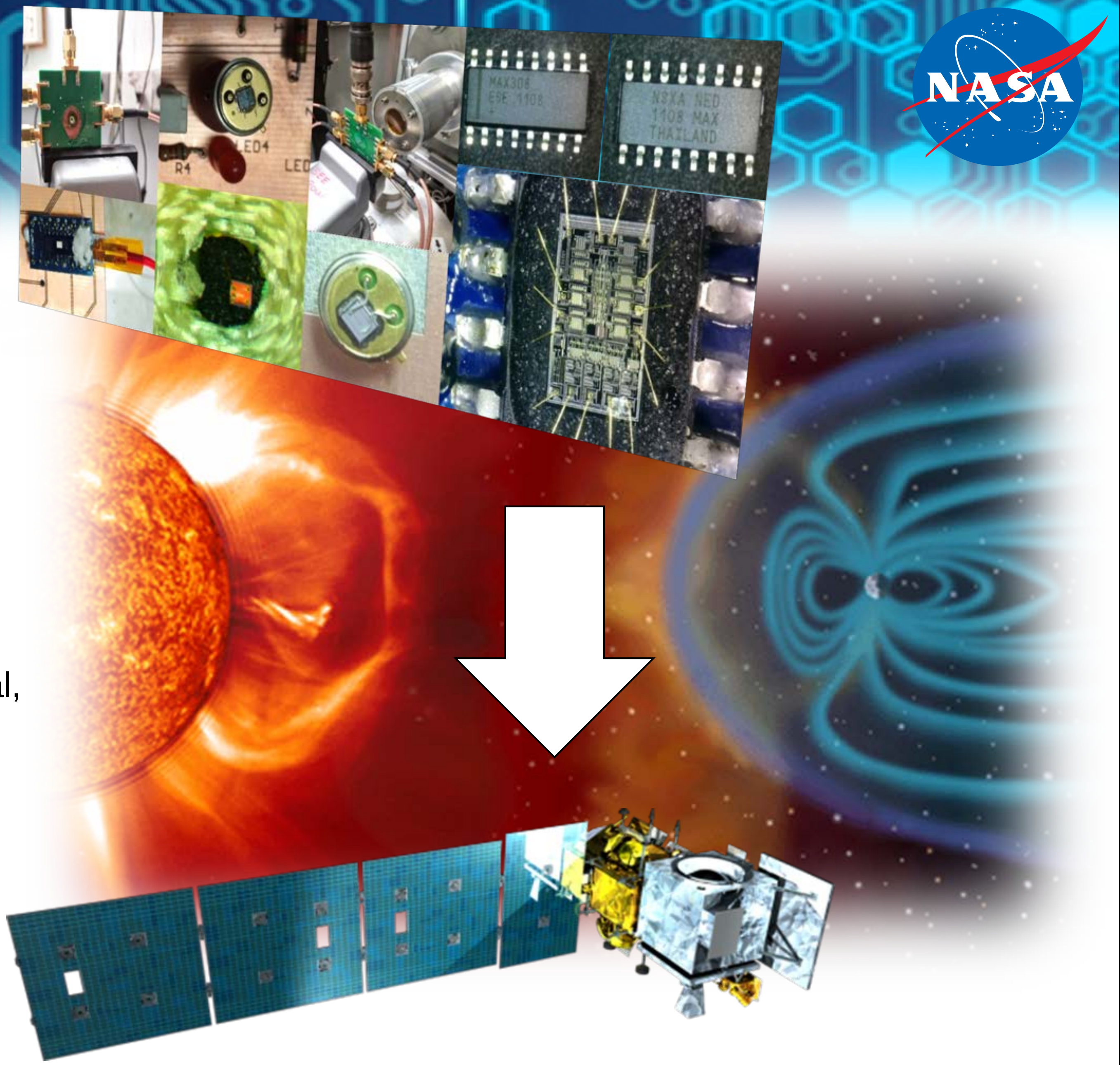
- Hardness Assurance is the practice of designing for radiation effects
- What it takes to overcome the radiation challenges
- Competing failure modes





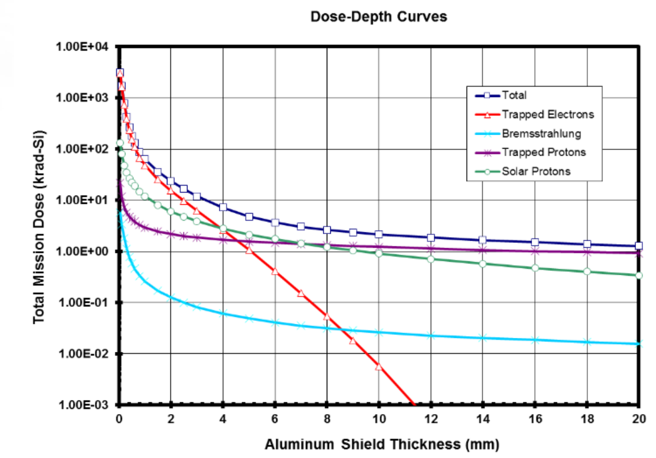
RHA Challenges… Not So Small

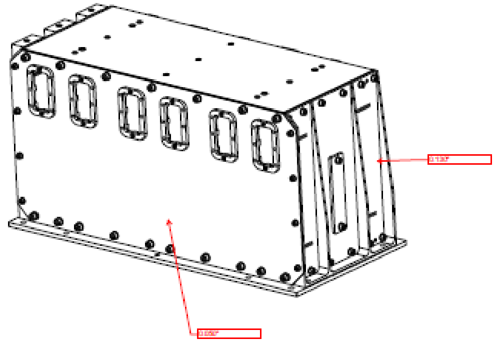
- New Technologies
  - Increased COTS parts / subsystem usage
  - Device Topology / Speed / Power
- Quantifying Risk
  - Translation of system requirements
  - Determining appropriate mitigation level (operational, system, circuit/software, device, material, etc.)
- Wide Range of Mission Profiles
- Always in a <u>*dynamic*</u> environment

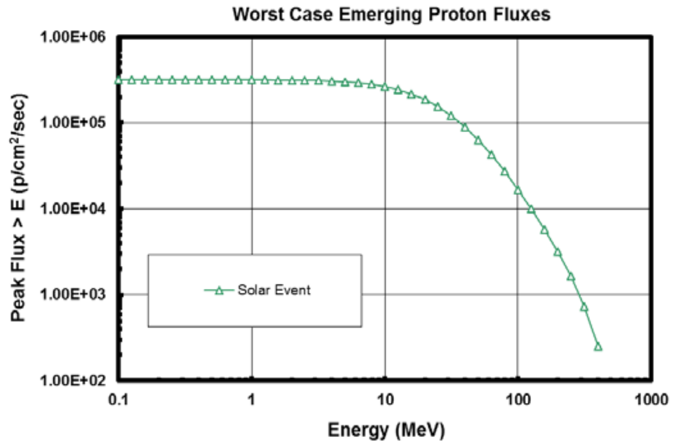


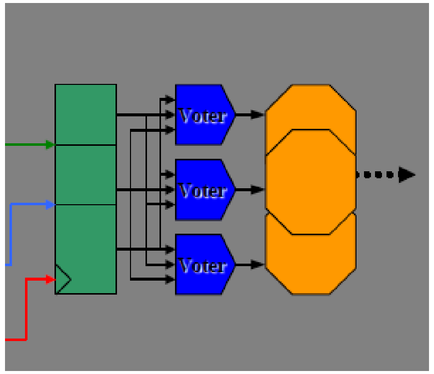
RHA Flow Doesn't Change With Accepted Risk

- **Define the Environment**
  - –External to the spacecraft
- **Evaluate the Environment**
  - –Internal to the spacecraft
- **Define the Requirements**
  - –Define criticality factors
- **Evaluate Design/Components**
  - –Existing data/Testing
  - –Performance characteristics
- **"Engineer" with Designers**
  - –Parts replacement/Mitigation schemes
- **Iterate Process**
  - –Review parts list based on updated knowledge









Define and Evaluate the Hazard

- Same process for big or small missions, no short cuts
- Know the contributions
  - Trapped particles (p+, e-)
  - Solar protons, cycle, events
  - Galactic Cosmic Rays
- Calculate the Dose
- Transport flux and fluence of particles
- Consider different conditions or phases of the mission separately

Free-Field Environment Definition → Shielding → Internal Environment Definition → Known Hazard

System → Sub-system → Parts

Derive Smart Requirements

- Requirements by Technology
  - By function or expected response (power, digital, analog, memory)
  - By semiconductor or fab (GaN, GaAs, SiGe, Si, 3D stacks, hybrids)
- Take into account the environment
- Take into account the application and criticality/availability needs
- Don’t overburden subsystems

Reliability Requirements

Operational Requirements

Performance Requirements

System → Sub-system → Parts

Quantifiable Risk

Engineering Trades / Parts Evaluation

- Weigh the hazard and risk
  - Mission parameter changes impact the radiation hazard
  - Look at each part's response, compare with part criticality
  - Utilize applicable data and the physics of failure
  - Determine if error will manifest at a higher level
- Be conscious of design trades
  - Size, Weight, and Power (SWaP) trades need to be carefully considered
  - Parts replacement/mitigation is not necessarily the best
  - **Single strain vs. allowable losses**

- When testing sparingly
  - The "we can't test everything" notion
  - Test where it solves problems and reduces system risk (risk buy down)
  - Requirements and risk impacts to the system should determine the order of operations when limited
  - Only when failure modes are understood can we take liberties to predict and extrapolate results

Radiation Hazard: TID and SEE

Environment

Mission Lifetime	LEO Equatorial (ISS)	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Moderate Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	High Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
1- 3 Years	Manageable Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
< 1 Year	Manageable Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	Moderate Dose / High GCR, High Solar Proton Variability

SmallSat Radiation Guidelines

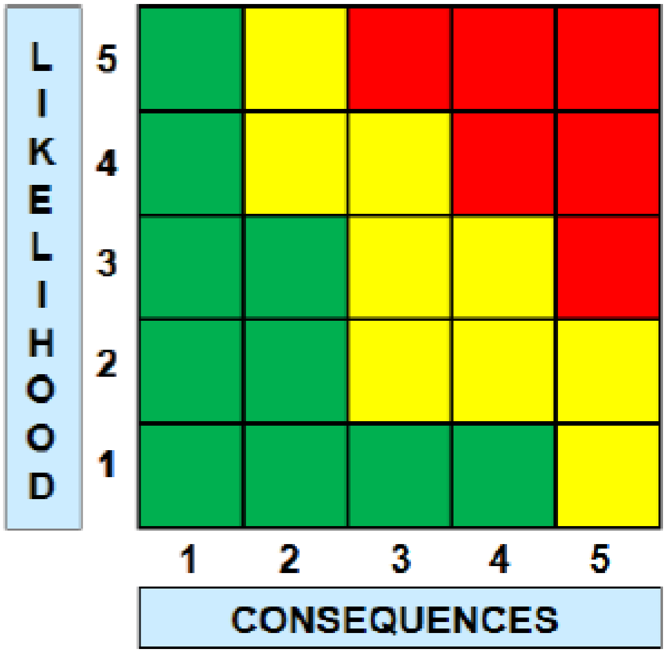
Mission Lifetime (With Assumed Risk Acceptance)	LEO Equatorial (ISS)	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Data on all SEE for critical parts, and have data on dose failure distribution on similar parts	Consider mission consequences of all SEE (Data for critical parts), have Dose failure distribution on lot	Have Data on all SEE, Have Data Dose failure distribution on lot
1- 3 Years	Have Data on DSEE for critical parts	Consider mission consequences of all SEE (Data for critical parts), have data Dose failure distribution on similar parts	Have Data on all SEE for critical parts, Have Data on Dose failure distribution on similar parts
< 1 Year	Look for data on DSEE for critical parts	Consider mission consequences of all SEE, and look for data on dose failure distribution on similar parts	Consider mission consequences of all SEE, and have data on dose failure distribution on similar parts

Environment (column headings); Mission Lifetime (With Assumed Risk Acceptance) (row headings)

NASA PG Reliability - Likelihood

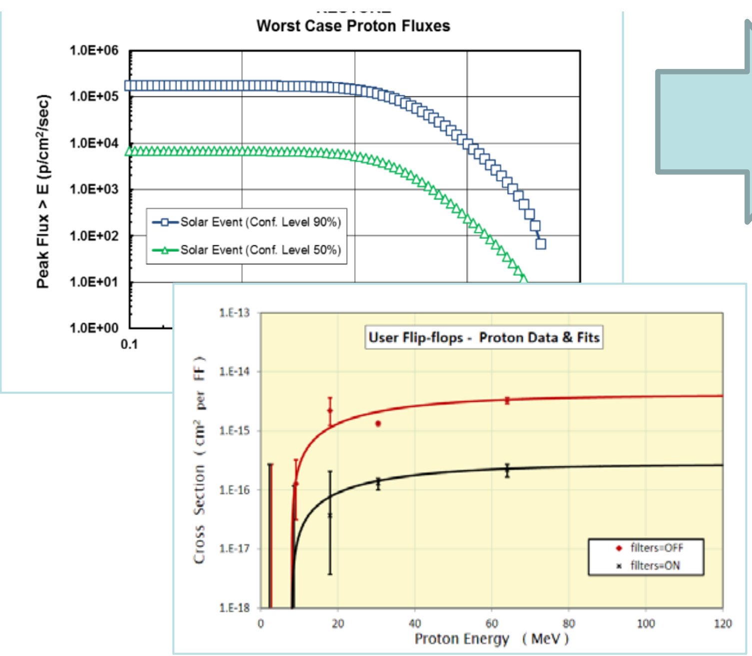
From Risk Assessment GPR 7120.4

Likelihood	**Safety** Estimated likelihood of Safety event occurrence	**Technical** Estimated likelihood of not meeting performance requirements	**Cost Schedule** Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$

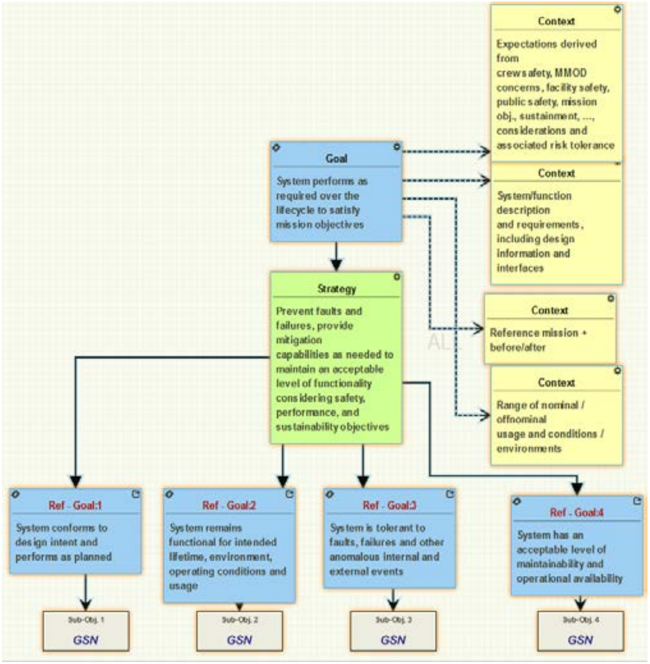


Model Based Systems Engineering

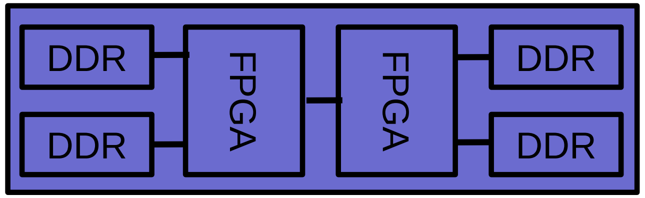
Environment & Design
- ***Environment Model and Test Data*** are brought together to get rates of upset / failure distributions
- ***Resources and Utilization*** are the scaling factors and criticality



Goal Structured Notation
- Concept of operations
- Requirements (***Availability***) are fed down correctly to subsystem
- Assumptions are tracked



Systems Modeling Language
- Description of System Connections / Dependencies
- Receives GSN readily



System Response & Trade Benefits

Acronyms

COTS	Commercial Off The Shelf
DD	Displacement Damage
GEO	Geostationary Earth Orbit
GSFC	Goddard Space Flight Center
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MBU	Multi-Bit Upset
MCU	Multi-Cell Upset
NEPP	NASA Electronic Parts and Packaging

RDM	Radiation Design Margin
RHA	Radiation Hardness Assurance
SEB	Single Event Burnout
SEDR	Single Event Dielectric Rupture
SEE	Single Event Effects
SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SOA	Safe Operating Area
TID	Total Ionizing Dose

Thank You

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- BACKUP Charts

Define and Evaluate the Hazard

- Define the Environment
  - External to the spacecraft
- Evaluate the Environment
  - Internal to the spacecraft
- Define the Requirements
  - Define criticality factors
- Evaluate Design/Components
  - Existing data/Testing
  - Performance characteristics
- “Engineer” with Designers
  - Parts replacement/Mitigation schemes
- Iterate Process
  - Review parts list based on updated knowledge

Environment Severity/Mission Lifetime

Evaluate RHA System Needs	Low	Medium	High
High	Manageable Dose / SEE impact to survivability or availability	Moderate Dose / SEE impact to survivability or availability	High Dose / SEE impact to survivability or availability
Medium	Manageable Dose / SEE needs mitigation	Moderate Dose / SEE needs mitigation	High Dose / SEE needs mitigation
Low	Manageable Dose / SEE do no harm	Moderate Dose / SEE do no harm	High Dose / SEE do no harm

Derive Smart Requirements

- **Define the Environment**
  - External to the spacecraft
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Environment Severity/Mission Lifetime

Criticality	Low	Medium	High
High	**Dose-Depth / GCR and Proton Spectra for typical conditions**	**Dose-Depth evaluation at shielding / GCR and proton Spectra for all conditions**	**Ray-Trace for subsystem / GCR and proton Spectra for all conditions**
Medium	**Dose-Depth / GCR and proton spectra for background**	**Dose-Depth / GCR and Proton Spectra For background**	**Dose-Depth evaluation at shielding / All spectra conditions**
Low	**Similar mission dose, same solar cycle / GCR spectra**	**Dose-Depth / GCR spectra**	**Dose-Depth / GCR and Proton Spectra For background**

Engineering Trades / Parts Evaluation

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
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Environment Severity/Mission Lifetime

Part Criticality	Low	Medium	High
High	Mitigate parameter drift / design to have upsets or resets occur	Add Shielding / Mitigation to have upsets or resets occurring	Add Shielding / Mitigation if known response Change parts or TEST
Medium	Accept change in precision parameters / allow upsets	Accept change in precision parameters / mitigate upsets allow for reset	Add Shielding / mitigation to have upsets or resets occurring
Low	Carry High Risk	Accept change in precision parameters / allow upsets	Mitigate parameter drift / design to have upsets or resets occur

Iterate the Process!

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
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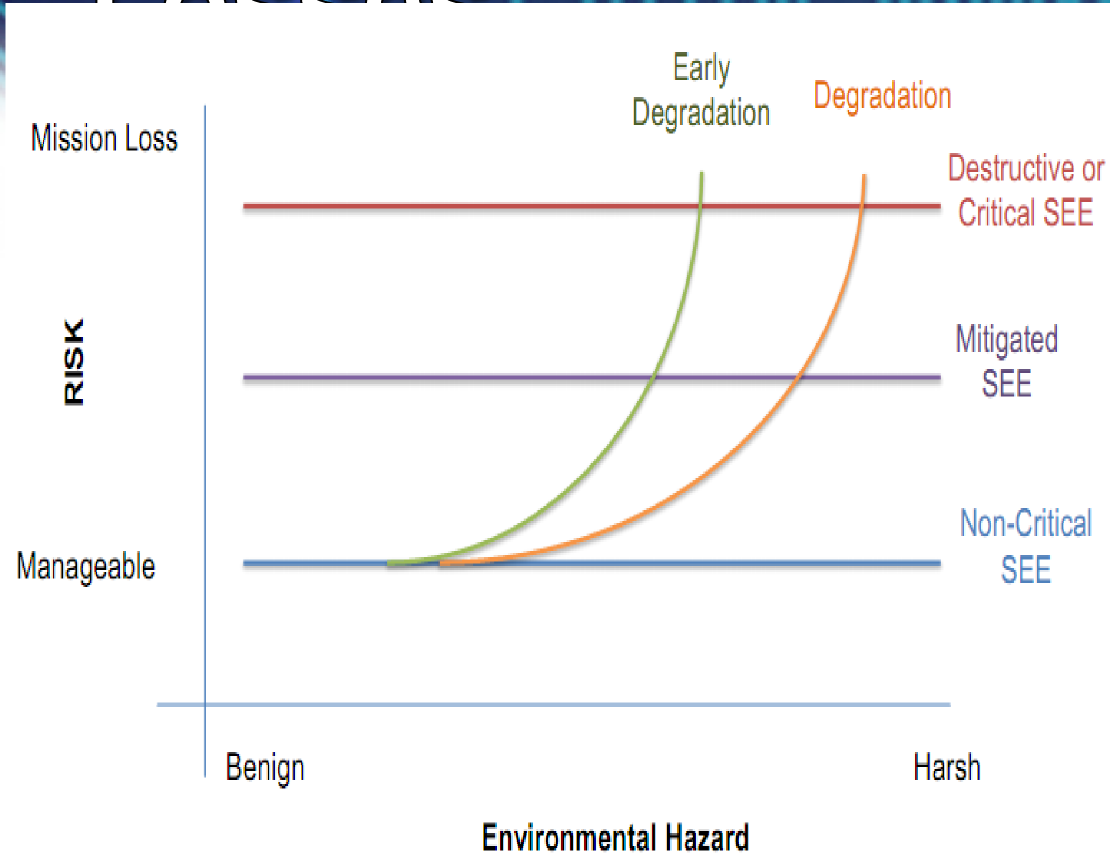
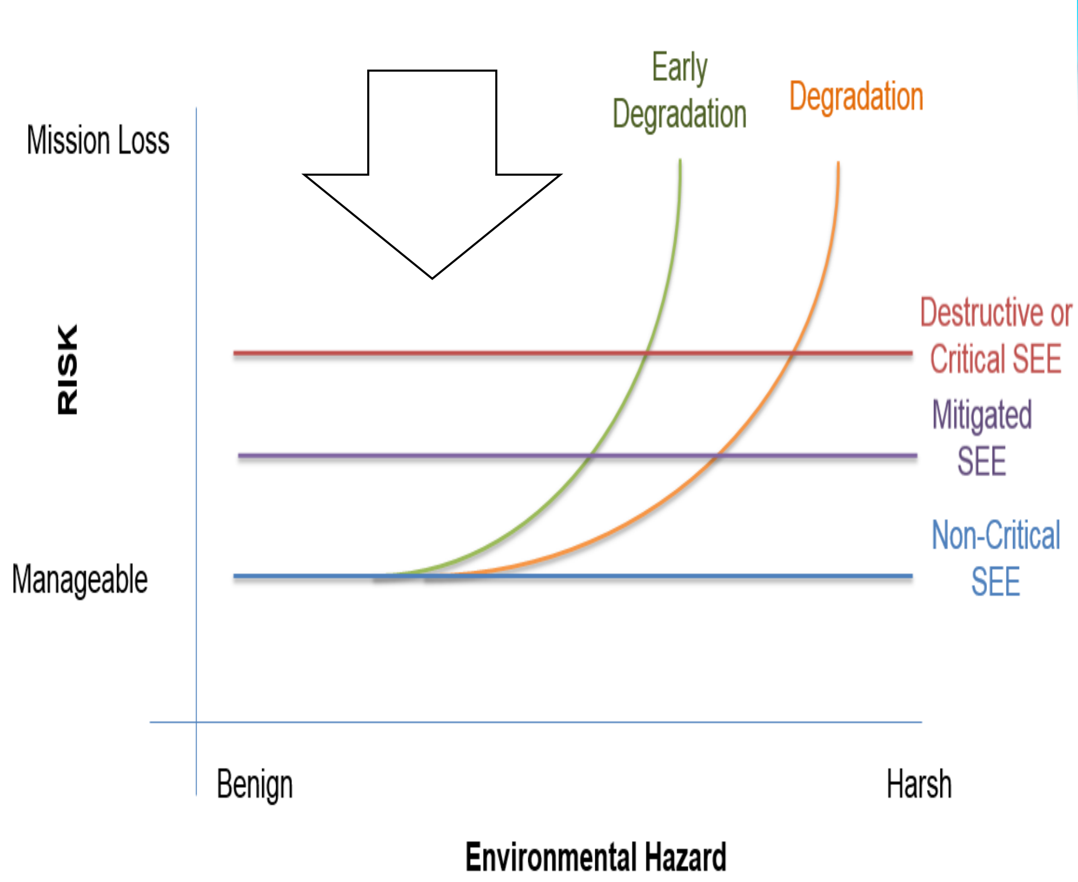
Single Strain vs. Allowable Losses

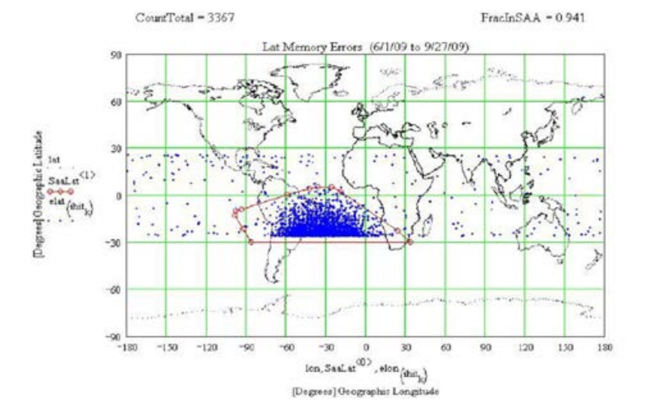


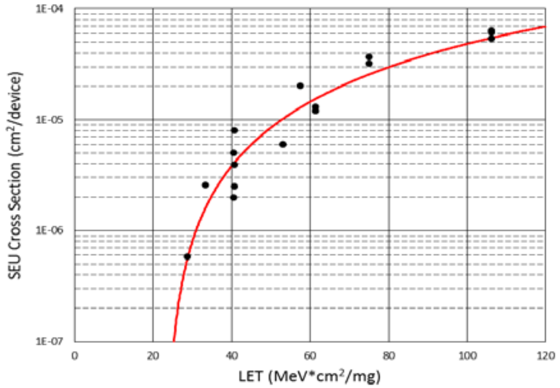


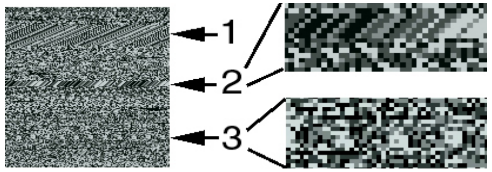
- Redundancy alone does not remove the threat
- Adds complexity to the design
- Diverse redundancy

Risk Hierarchy and Classification

- Parts
  - Predicted radiation response
  - Downstream/peripheral circuits considere
- Subsystem
  - Criticality
  - Complexity
  - Interfaces



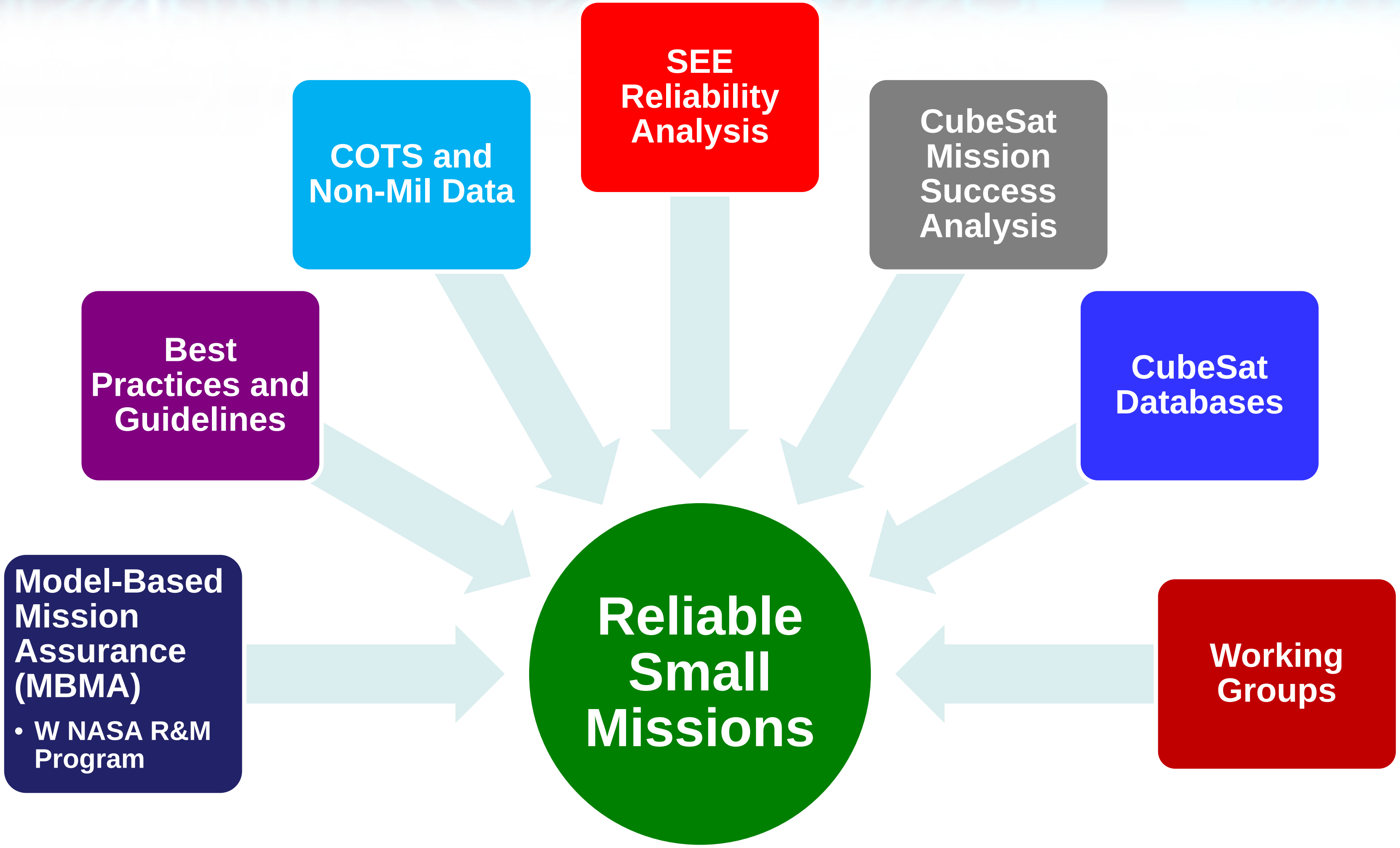




- System
  - Power and mission life
  - Availability
  - Data retention
  - Communication
  - – Attitude determination

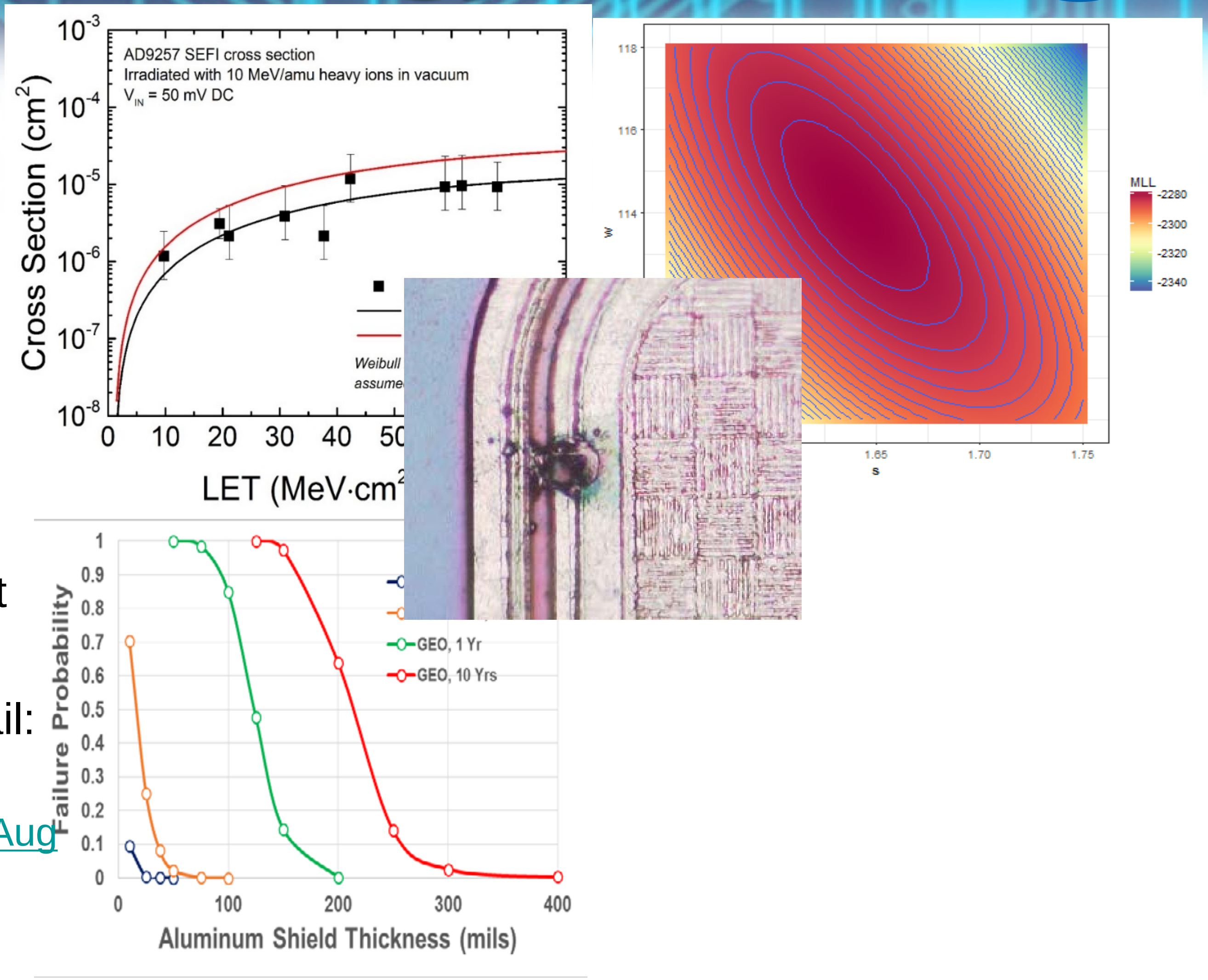
In-Flight Evaluation

- Key to future mission success
- Feeds back into our efforts



Requirements by Technology

- SEE, SET
  - Confidence intervals for rate estimations
- SEL, SEB
  - Environment driven, risk avoidance
  - Protection circuitry / diode deratings
- SEGR, SEDR
  - Effect driven, normally incident is worst case
  - Testing to establish Safe Operating Area (SOA)
- MBU, MCU, SEFI, Locked States
  - Only invoked on devices that can exhibit the effect
  - Watchdogs / reset capability
- Proton SEE susceptible parts need evaluated in detail:



https://nepp.nasa.gov/files/25401/Proton_RHAGuide_NASAAug09.pdf

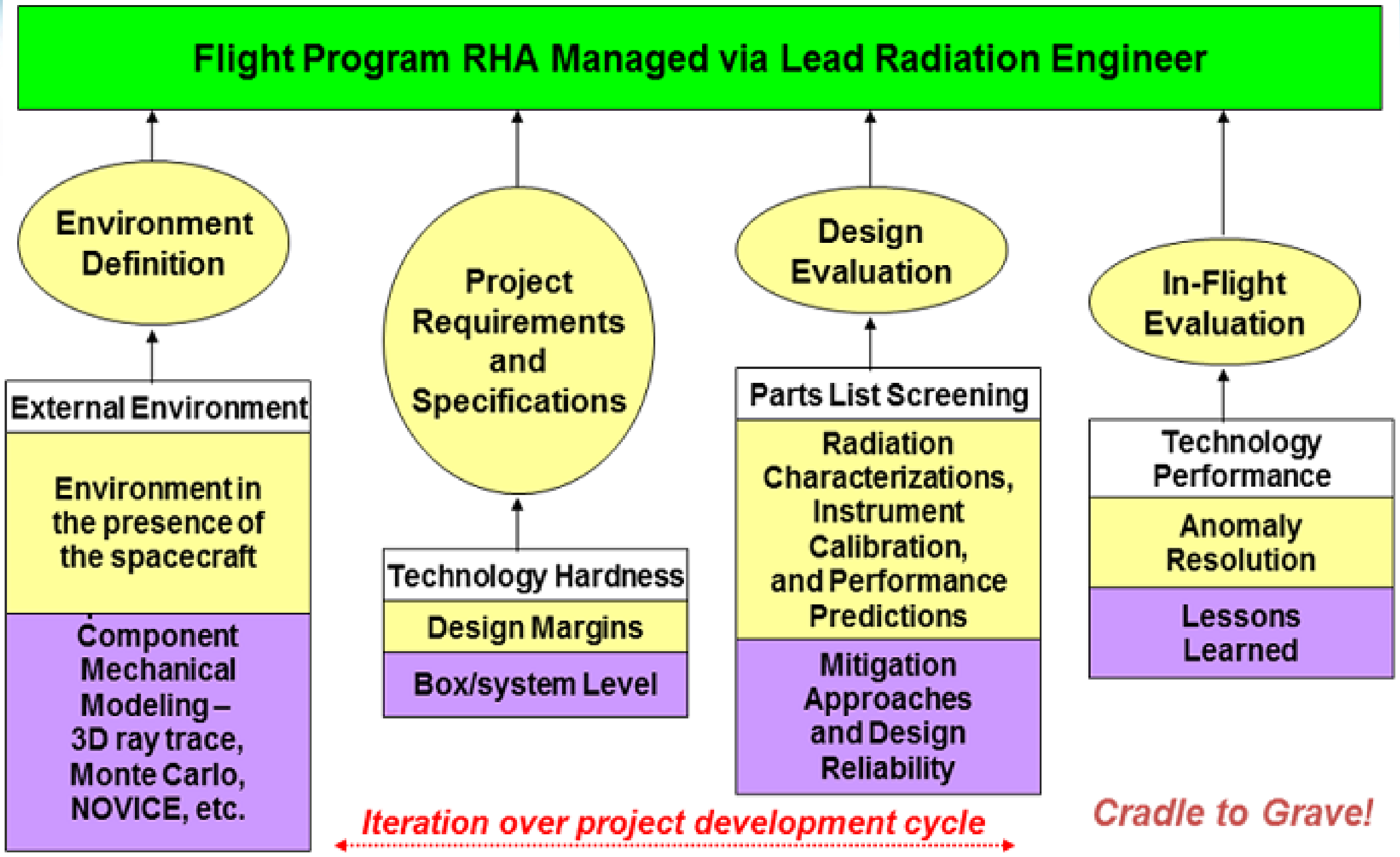
Summary of Environmental Hazards

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
International Space Station	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	Yes	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration – Lunar, Mars, Jupiter	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Possibly	Yes	Maybe	No	Yes	Yes

https://radhome.gsfc.nasa.gov/radhome/papers/SSPVSE05_LaBel.pdf

RHA Definition and Overview

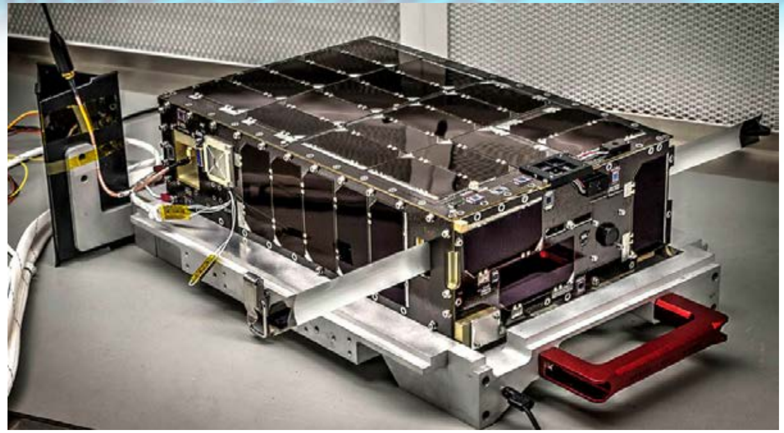
RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *design* specifications throughout exposure to the mission space environment



(After Poivey) (After LaBel)

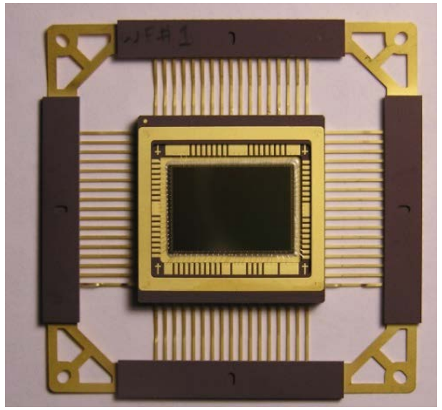
Risk Acceptance

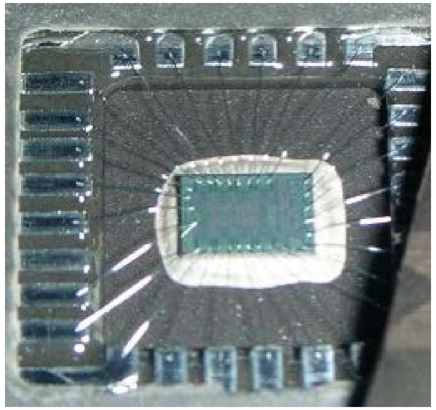
- Mission Profiles Are Expanding
  - Profiles were based on mission life, objective, and cost
  - Oversight gives way to insight for lower class
  - Ground systems, do no harm, hosted payloads
  - Similarity and heritage data requirement widening
  - In some cases **<u>unbounded radiation risks are likely</u>**



Credits: NASA's Goddard Space Flight Center/Bill Hrybyk

- Part Classifications Growing
  - Mil/Aero vs. Industrial vs. Medical
  - Automotive vs. Commercial





As a Result, Risk Types Have Increased and RHA is Necessary!

Summary

- RHA for Small missions
  - Challenges identified in the past are here to stay
  - Highlighted with increasing COTS usage
  - Small missions benefit from detailed hazard definition and evaluation
- RHA flow doesn't change, risk acceptance needs to be tailored
  - We need data with statistical methods in mind
- Varied mission environment and complexity is growing for small spacecraft
  - Don't necessarily benefit from the same risk reduction efforts or cost reduction attempts
- Requirements need to not overburden
  - Flow from the system down to the parts level
  - Aid system level radiation tolerance
- Risks versus rewards can have big impact on mission enabling technologies

Sponsor: NASA Electronic Parts and Packaging (NEPP) Program